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INFRARED EXCESS OF RY SGR

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ABSTRACT

A large infrared excess has been found for RY Sgr, an R CrB–type variable star. During a recent 8-month interval the visual brightness increased, while the radiation in the infrared, in the 2–3.4-μ region decreased. These observations support the general model for R CrB proposed by Stein *et al.*, in which the infrared flux is ascribed to blackbody radiation from a circumstellar cloud of particles ejected at the time of deep minimum.

Stein *et al.* (1969) have recently reported a large infrared excess for the hydrogen-poor, carbon-rich variable R CrB. They suggest that this excess is due to blackbody radiation from a cloud of particles at a temperature of 940° K. At the epoch of their observation the visual magnitude of R CrB was 0.6 mag fainter than at maximum, and this deficiency in the visual flux is just the amount observed in the infrared excess. If their model is correct, a cloud with an angular radius of 0".07 would be required, and the above authors propose that such a cloud could have formed by the ejection of particles during the past deep minimum (about 6 years ago). In a general way these ideas are consistent with the Loreta-O'Keefe hypothesis of carbon-particle formation (Loreta 1934; O'Keefe 1939) to explain the deep minima of R CrB–type stars, and this hypothesis has received other support from extensive (and continuing) spectroscopy by a group at the Cape and Radcliffe Observatories. These results will be discussed in full at a later date; those prior to mid-1968 have been summarized by Feast (1969). We are reporting here some visual and infrared observations of RY Sgr, another R CrB–type star. With some qualifications, these data tend to support the model proposed by Stein *et al.* (1969).

Our observations, obtained with the photometric facilities of the Lunar and Planetary Laboratory of the University of Arizona at two distinct epochs, are given in Table 1. In addition to the observed magnitudes, the filter designations and their effective wavelengths (Johnson *et al.* 1966) are also given. With the exception of the M (5 μ) and N (10.2 μ) magnitudes, all values represent the mean of two or more independent observations. The data were obtained at two epochs, October 1968 and June 1969. From the observations in Table 1 it is evident that RY Sgr, like R CrB and υ Sgr (Lee and Nariai 1967), a star which shares with the R CrB variables a large deficiency of hydrogen, also exhibits a large excess of radiation at long wavelengths. This excess is truly a significant one: the $K - L$ color, $\sim$2.0 mag, can be compared to $+0.8$ mag, the value found for the most highly reddened of a sample of M-type supergiants (Lee 1969), while the $K - M$ index $>+4.0$ mag, is larger than that found for most infrared stars, including NML Cyg (Johnson, Mendoza V., and Wiśniewski 1965). The variability indicated in the data is also important for the theory of these stars. At the time of the June 1969 observations the star was brighter in the visual region than in October 1968 but *fainter* in the infrared, from 2.2 to 3.4 μ.

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In Figure 1 we have plotted the spectral energy distribution (log F_ν [W Hz^{-1} m^{-2}] versus log ν) for RY Sgr, as computed from the data in Table 1 and the absolute calibration of Johnson (1966). The observations of R CrB from Stein *et al.* (1969) are also shown. The error bars on the 5- and 10.2-μ points are estimates of the probable errors of the single observation; the errors of the other points are approximately 10 percent and are due primarily to uncertainties in the calibration. The long-wavelength flux for RY Sgr is seen to be greater than that of R CrB, although the latter was 1.9 mag brighter in the visual when the observations were made. Because of uncertainties in the intrinsic intensity distribution of the stellar continuum and in the operative law of reddening for these stars, the stellar contribution to the total radiation of RY Sgr can only be approximated. The spectrum of a G0 Ib star (Johnson 1966) reddened by E_{B-V} = 0.45 mag

TABLE 1

PHOTOMETRY OF RY SGR

Filter	$\lambda_0(\mu)$	Magnitudes: October 8, 1968 (J.D. 2440138)	Magnitudes: June 4, 1969 (J.D. 2440377)
U	0.36	+10.91	+10.34
B	0.45	+10.01	+ 9.49
V	0.55	+ 8.86	+ 8.31
R	0.70	+ 7.98	+ 7.39
I	0.90	+ 7.37	+ 6.82
J	1.25	+ 6.43	+ 6.29
H	1.62	+ 5.50	+ 5.46
K	2.2	+ 4.02	+ 4.31
L	3.4	+ 2.05	+ 2.26
M	5.0	...	+ 0.04
N	10.2	...	− 0.17

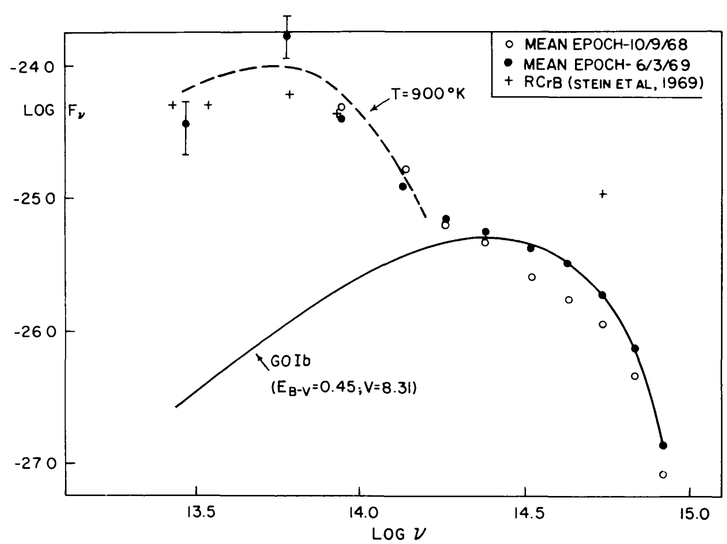

FIG. 1.—Spectral energy distribution of RY Sgr. Filled and open circles refer to observations made at different epochs. Solid line represents a reddened G0 Ib star normalized to V = 8.31 mag; dashed line is the distribution of a 900° K blackbody. Crosses represent the observations of R CrB by Stein *et al.* (1969).

and normalized to $V = 8.31$ mag fits the blue and visual points of the June distribution very well (see Fig. 1). This approximation for the stellar continuum (and it must be considered only an approximation because of the great range in *UBV* colors and spectral peculiarities exhibited by these stars in the course of their cycles) contributes only 20 percent of the total observed flux of RY Sgr. The corresponding fraction for R CrB (assuming a 6000° K blackbody) was 60 percent. With $V_{max} = 6.5$ mag for RY Sgr, the visual (stellar) radiation is lower by 1.8 mag (in June), or about 80 percent lower than its maximum value. RY Sgr therefore seems to fit the model given by Stein *et al.* (1969) for R CrB.

Additional support for the model of Stein *et al.* is seen in the variability of RY Sgr. As the visual flux increases, the radiation in the infrared decreases and the total luminosity of the star tends to be conserved. Because the 5- and 10.2-μ observations are lacking for the October epoch, we are unable to say categorically that the total flux has not changed, but this is a distinct possibility. The total flux at log $\nu > 13.9$ has increased by less than

TABLE 2

CIRCUMSTELLAR CLOUDS FOR RY SGR AND R CRB

Parameter	RY Sgr	R CrB
V_{max}	+6.5 mag	+5.8 mag
$M_{V(max)}$	−4.0 mag	−4.0 mag
A_V	0.4 mag	0.2 mag
Distance	1 kpc	0.8 kpc
Cloud angular diameter	0″.020	0″.014
Cloud radius	10 a.u.	5 a.u.
Cloud temperature	~900° K	~940° K
Cloud luminosity	2.8×10^3 $L_\odot$	0.9×10^3 $L_\odot$
Mean expansion velocity	25 km sec^{-1}	4 km sec^{-1}

10 percent during the interval separating our observations, and this increase could easily be compensated for by a small-percentage change at lower frequencies. Yet the situation may be more complex, since the rising branch of RY Sgr is also characterized by periodic or quasi-periodic fluctuations (~37-day period). Our data do not reveal whether the infrared intensity follows these short-period variations (in antiphase) or simply mirrors the mean visual-light level at a given epoch.

The fact that RY Sgr and R CrB exhibit similar photometric properties is not surprising, since they are spectroscopically very similar at maximum visual light (Danziger 1965). If we assume an absolute magnitude of $M_V = -4.0$ for R CrB–type stars (W Men in the Large Magellanic Cloud indicates that they may actually be brighter than this; Feast 1956), as well as estimates of the visual extinction of 0.4 and 0.2 mag for RY Sgr and R CrB (from the distribution of reddening in the Galaxy: FitzGerald 1968), we can determine the distances and other parameters that characterize the circumstellar clouds around these stars. This information is summarized in Table 2. The infrared energy distribution of RY Sgr suggests a temperature of less than 1000° K; the 900° K curve shown in Figure 1 does not fit the observations exactly, but the discrepancies may be due to the uncertainty in the 5- and 10.2-μ measurements. The expansion velocity is the mean velocity required to move the particles to the radius of the cloud, on the assumption that they were ejected at the epoch of the last deep minimum (~6 years ago for R CrB; ~23 months ago for RY Sgr).

While the essentials of the model of Stein *et al.* (1969) fit well the observations of RY Sgr and R CrB, several questions remain to be answered. For instance, if the circumstellar material was ejected during the past deep minima with comparable velocities in each case, why is not the radius of the R CrB cloud larger than that for RY Sgr? It is rather surprising that one should have to postulate a mean expansion velocity six times greater for RY Sgr than for R CrB. If the computed radii of the clouds are approximately correct, then the temperature of the R CrB cloud should be considerably higher than that of the RY Sgr cloud. The present data do not allow an accurate determination of the temperature, and this, no doubt, is part of the problem.

At least four explanations of the present observations are possible: (1) The cloud around R CrB is smaller because it is now contracting gravitationally, having passed through some maximum radius at an earlier time. The importance of taking into consideration the gravitational deceleration has been pointed out to us by Dr. V. Myerscough. (2) Perhaps most of the material in the clouds (possibly graphite particles) was rapidly expelled at the time of deep minimum to some critical radius and thereafter has persisted or has been replenished at this distance. In fact, evidence for the ejection of matter with velocities up to about 200 km sec^{-1} has been found from (gaseous) absorption features (Feast 1969). (3) The clouds could form at their present positions at the time of deep minimum (although this might pose problems in interpreting the "chromospheric" emission spectrum found during the initial decline, since this apparently lies above the layers of absorbing particles). In any case, alternatives 2 and 3 suggest that a portion of the cloud could be quasi-stationary in nature, in which case long-wavelength radiation from this component would cause the energy distribution of the star to be noticeably nonstellar at all times. Large variations in the infrared flux could arise from small-percentage changes in the effective radius or from structure within the cloud. At maximum visual light, however, the stellar continuum may account for most of the radiation. (4) The derived cloud radii are minimum values. Should the clouds be broken up into cloudlets filling only a fraction of the shell, then the radii would be much greater than those calculated. Thus the shell around R CrB could in fact be the same size or larger than that surrounding RY Sgr. Although many problems remain, the present work strongly supports the hypothesis of reradiation from a circumstellar cloud.

The 5- and 10.2-μ observations of RY Sgr were obtained with the cooperation of F. J. Low, who allowed us to use his helium-cooled germanium bolometer, and D. E. Kleinmann, who assisted in making the observations. We gratefully acknowledge their assistance in this regard.

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